Advanced Hot Bonding System For Repair Of Aerospace Structures

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Abstract

Repair techniques play an important role in increasing the useful life of the aerospace structures. They increase the confidence level of the user and promote the application of composites. Among the various repair techniques, hot bonding is widely acclaimed for its ability to restore the strength close to the original values. It is used for the repair of metal or composites structures. Hot bonding performed using flexible heater blanket and vacuum bag is the most suitable method for in-situ repair.

Hot bonding is performed through elevated temperature cured adhesive system, which increases the glass transition temperature and hence the service temperature of the final product. These adhesive systems are sensitive to temperature gradient. If the gradient exceeds ±5^oC, the cross-linking process and the quality of repair is adversely affected. In the hot bonding process, only the repair area is heated and the rest of the part is left in atmospheric condition. Due to partial heating, the region below the centre of the heater gets hotter than the surrounding. This problem worsens if the job has skin and spar construction or has non-uniform cross-section as in the case of aircraft control surfaces or windmill blades. The hot bonding equipment currently being imported (none manufactured within India) does not ensure temperature uniformity.

This paper discusses the design and development aspects of multi-zone, portable hot bonding equipment, which overcome the above problems. Multiple numbers of appropriately placed heater blankets, sensors and a data acquisition device coupled with a novel control algorithm and multi-threaded software has resulted in the portable and reliable hot bonder. The equipment was tested on typical aircraft parts, such as an aluminium rudder and a composites fin tip. The conventional single heater blanket method has resulted in a temperature gradient of over 12^oC, while this product has limited the temperature gradient to within ±1.5^oC.

1.0 INTRODUCTION

Aircraft structures whether made of alloy or composites do get damaged during service due to many unavoidable reasons. Damages can be repaired either in situ or in a lab depending on their severity, size and location. In situ repairs are advantageous as they can be performed quickly and without dismantling the defective part.

Hot bonding is an in situ repair technique that closely restores the original structural characteristics by the use of high temperature cured adhesive and vacuum bag. It can be used to bond a pre-cured composites laminate or a metal sheet on the damaged area or simultaneously cure and bond a wet patch. In this process, only the repair area is heated by direct conduction from a flexible heater blanket enclosed in a vacuum bag. By evacuating the air from the vacuum bag, atmospheric pressure is made to act on the heater and repair area thereby ensuring good heat conduction, compaction and removal of gases emanated during polymerisation.

Hot bonding process creates temperature gradient due to number of reasons that include partial heating, (structure surrounding the repair area is at atmospheric temperature), non-uniform cross-section, varying skin thickness, skin and spar construction or sand-which construction etc. If the temperature gradient exceeds about 8^oC the cross-linking process and therefore the repair quality is affected drastically.

2.0 EXISTING METHODS TO MINIMISE TEMPERATURE GRADIENT

2.1 Selection Of Control Sensor

The hot bonding equipment currently being imported (none produced within India) control the temperature based on one of the following methods, which are operator selectable.

- Lagging or leading temperature sensor
- Any of the selected temperature sensor
- Average of a group of temperature sensors

All of the above methods, including the ‘average value control’ fail to correct the temperature gradient.

2.2 Patterned Heaters With Non-Uniform Heat Dissipation

Specially patterned heaters whose watt-density is not uniform, but matched to the thermal characteristics of the part under repair can control the temperature gradient. However, such heaters are very expensive to fabricate and this method requires complete knowledge about the defective part and its thermal characteristics. Hence, this method is impracticable.

2.3 Thermal Insulation And External Infra Red Heating

In this method a thermal survey is conducted before the actual repair. After analysing temperature gradient, heat insulators in the form of thin, flexible sheets are placed between the heater and the hotter region to reduce the heat flow and Infra red lamps are shined over the colder regions to increase the heat flow. Essentially, these are manual methods that require constant attention and yet result in poor control and inconsistent cure.

3.0 ADVANCED HOT BONDING WITH MULTI ZONE HEATERS

In the advanced hot bonding method the damaged area is heated with number of small heaters, which are controlled independently through a closed loop control system. Electrical power to each heater is varied based on the real time temperature data acquired at multiple locations across the damaged area. This technique provides completely automatic and job-independent temperature gradient control without demanding a thermal survey or prior knowledge about the job.

3.1 Heater Arrangement

Heating the structure with more number of smaller heaters can minimize temperature gradient. However, for closed loop control each heater requires at least one sensor and one SSR. This would increase the number of analog inputs and digital outputs to be interfaced with the controller. Placing large quantity of sensors and heaters and connecting them carefully for every repair is a tedious work. With lesser number of heaters the major constrain is that the temperature gradient within one heater area cannot be controlled. Considering the temperature gradient present in typical aircraft structures, as an engineering compromise between complexity and application demands, a five-zone heater control was chosen. For a typical repair area of 80mm X 80mm a 100mm x 100mm heater was used for the inner region surrounded by 50mm x 150mm heater on all sides. Fig.1 shows the prevailing single heater arrangement and the new five-zone heater arrangement to limit the temperature gradient.

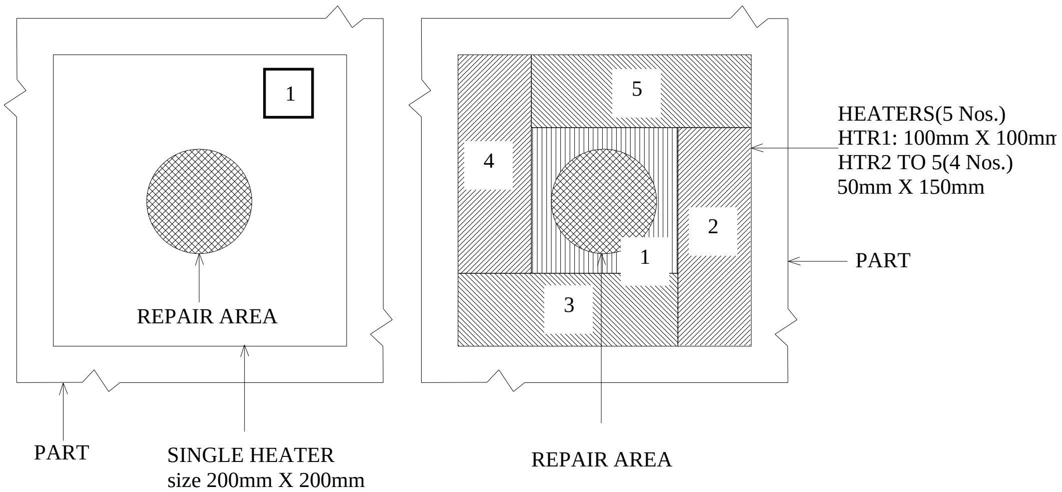

Fig. 1: Single Heater And Five-Zone Heater Arrangement

3.2 Design Goals

The goal of Design and Configuration is to solve the following major problems arising in cure control of bonded repairs.

- Rate of heating/cooling, dwelling time and temperature gradient control
- Measurement and control of vacuum
- Hardware minimization to achieve portability and reliability

- Cure cycle programming, execution and documentation.

3.3 Construction

The major hardware was realized using a Notebook computer and an USB based Temperature / data logger card having 14 analog channels and 8 digital channels. The other hardware include signal conditioners for thermocouples with built-in-Cold Junction Compensation (CJC) and Auto Zero channels and an array of eight optically isolated Solid State Relays (SSR) that controls the AC supply to the heater blankets and the vacuum control valves. The simplified block schematic is shown in fig.2. Silicon insulated flexible heater blankets of size 100mm x 100mm (1 no.) and 75mm x 150mm (4 nos.) were used to heat the repair area of 200mm x 200mm.

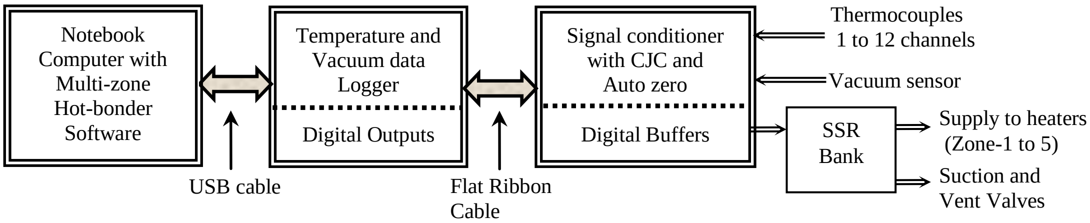

Fig. 2: Block Schematic Of Advanced Hot Bonding System

The software was developed using the Microsoft Visual C++ compiler on Windows platform. In addition to performing the unique control functions explained above, the software provides for complete SCADA (Supervisory Control and Data Acquisition) features including numerical/graphical data display or print out either on-line or off-line. Fig.3 shows the photograph of the hot bonding equipment with heater blankets.

3.4 MIMO (Multi Input Multi Output) Temperature Gradient Control Algorithm:

The Multi-zone temperature control algorithm accepts up to twelve thermocouples configured as two per zone and two standbys. It controls five heaters simultaneously and can affect their status once in every 0.5 second.

The user's cure program consists of heat up ramp, soak time, cool down ramp etc, which essentially defines the required uniform temperature in the repair area as a function of time. Accordingly, set-points (SP) are generated once in a fixed time interval known as scan interval. Scan interval was determined according to the maximum rate of heating, display resolution and the time required by data logger card for digitising all the analog channels etc., and it was fixed as five seconds. During every scan interval all the temperature channel data are acquired. Control sensor for each zone can be selected as any one of the two sensors, the leading sensor, the lagging sensor or the average of both the sensors. This value forms the Process Variable (PV) of the given zone.

The SP and the working PV of each zone are passed on to individual PID loops. Five PID loops are run simultaneously. Every PID loop determines the control output for that particular zone, based on the pre-programmed PID constants. The normalized control output is computed in percentage, that is 0-100% with 0 indicating no heating power and 100% indicating full heating power demand. To feed the PID control output (0 to 100%) and to vary the heater power between 0 to 100% a DAC (Digital to

Analog Converter) card and a phase-angle fired SCR module are required respectively. These devices have been eliminated through a cycle time control program. It converts the linear control output into a pulse width modulated digital signal. This approach requires only a digital output device and a Solid-State Relay (SSR) for every heater. Based on the demand heaters are switched in steps of 0.5second interval. For example, if the heat demand is 50% then for half of the scan interval heaters will be ON. The ON and OFF pulses are properly interleaved to achieve smooth change in temperature. The software repeats set point calculation, PV calculation, PID algorithm and cycle time control loop for every five seconds.

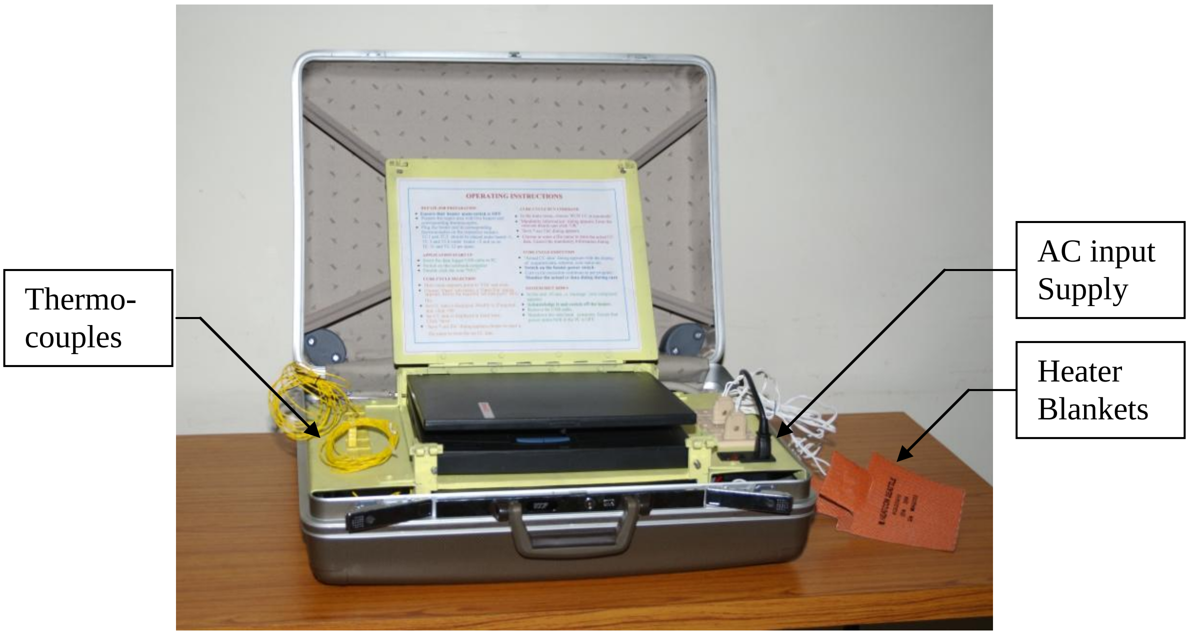

Fig. 3: Photograph Of The Multi-Zone Hot Bonding System

4.0 TESTS AND RESULTS

4.1 Thermal Survey On A Composites Fin Tip

An aircraft fin tip was considered as a typical composites specimen for thermal survey. This part is made of glass fibre reinforced plastics. The repair area chosen is partly on a rib. A defect of size 80 mm diameter and a heater size of 200mm x 200mm was considered. One thermocouple was placed in the centre for controlling and four were placed on the edges for monitoring. All the sensors were located well within the heater area of 200mm x200mm. Vacuum bagging and air evacuation was carried out with out prepreg. The cure cycle chosen consists of heating at a rate of 8^{o}C/min. from ambient temperature to 120^{o}C, holding at 120^{o}C for 24 minutes, heating at a rate of 8^{o}C/min from 120^{o}C to 176^{o}C, holding at 176^{o}C for 24 minutes, cooling at a rate of 8^{o}C/min from 176^{o}C to 100^{o}C and finally holding it at 100^{o}C for 24 minutes. Throughout the cure a constant vacuum of less than 40 torr was maintained. The temperature data plot of the control sensor, leading and lagging sensors are shown in Fig.4. It is found that a temperature gradient of about 12^{o}C exists between the leading sensor and the lagging sensor. The same experiment was repeated using the five zone hot bonder with five heaters arranged as shown in fig.1 and the data are plotted in fig.4. It is found that the temperature gradient has been brought down to about 1.5°C throughout the cure.

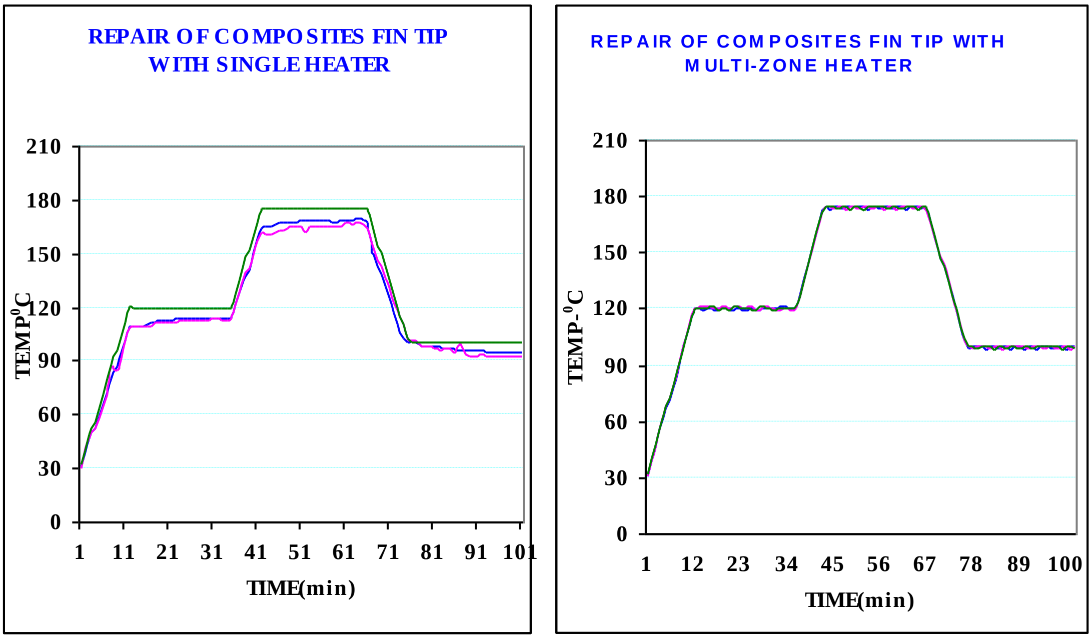

Fig. 4: Temperature Gradient In A Composites Fin Tip With Single And Multi Zone Heaters

A thermal survey using multi zone hot bonder with five heaters was carried out on a typical aircraft rudder made of aluminium alloy. This part has two thin skins bonded to either side of a honeycomb structure and forms an aerofoil cross-section. Sensor placement and Cure cycle programming was carried out as indicated in the previous experiment. The PID constants obtained for composite part was retained. The temperature data acquired from the control sensor, leading and lagging sensor are plotted in Fig.5. The results indicate that a temperature gradient of less than 1.5°C has been realized and the hot bonder works well with both metal and composite parts without changing the PID constants.

Typical screen shots of the cure cycle programming page and Programmed Cure Plot are shown in Fig.6

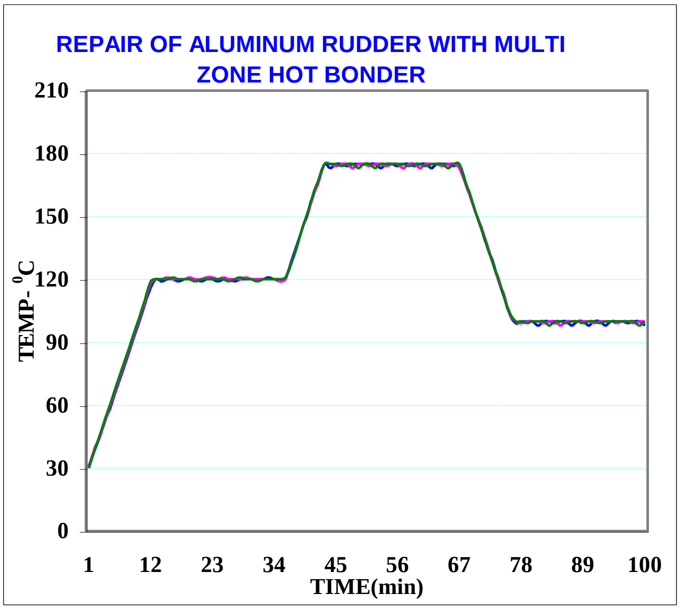

Fig. 5: Temperature gradient in a typical aluminium rudder with Multi-zone Heaters

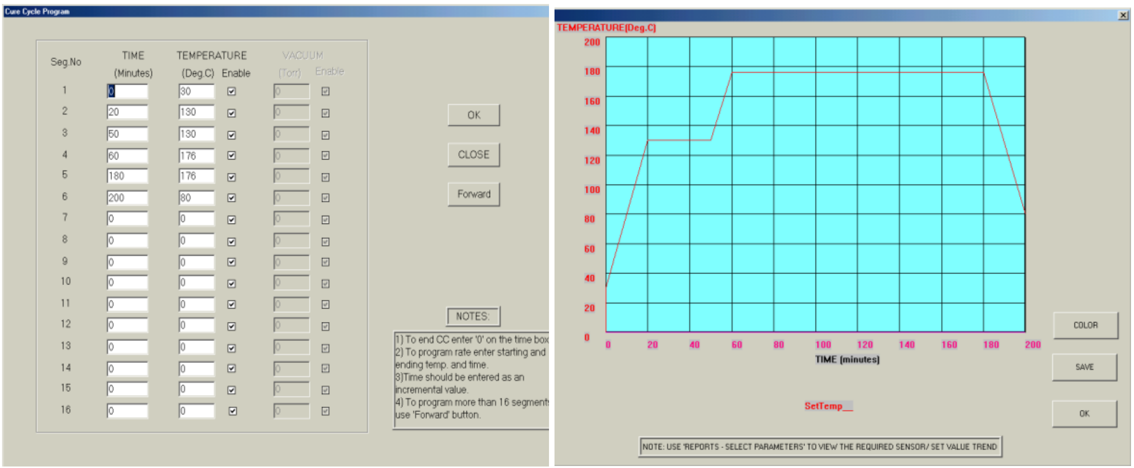

Fig. 6: Cure cycle programming page and Programmed Cure Plot

5.0 CONCLUSION

A multi zone hot bonder, which is not available in the international market has been designed and developed successfully at a relatively low cost by realizing most of the functionalities through the custom built software. A novel multiple heater placement technique has been conceived and implemented successfully for automatic spatial temperature gradient control. A Multi-Input, Multi-Output temperature control algorithm has been implemented for twelve inputs and five outputs control system. This algorithm was tuned to execute five PID loops such that they all maintain the same temperature in spite of different heat demand and non-optimal PID values. A user friendly, menu driven application software has been developed using Visual C ++. It executes five simultaneous PID loops and provides tamper-proof data reports both in numerical and in trend form. Typical hot bonded repairs have been performed on aluminium and composites aircraft structures and the temperature gradient was found to be within +/-1.5^{0}C. This product has been supplied to M/S. Indian Air Force for field trials. Successful hot bonding trials have also been carried out on Advanced Light Helicopter parts at M/s.Hindustan Aeronautics Limited, Bangalore.

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